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BTeV C0 IR Quadrupole Magnet Inner Strand Specification

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Abstract:

This note contains the specification of the inner strand for the BTeV C0 IR Quadrupole Magnets. This specification was part of a package consisting of: Inner and Outer Cable Manufacturing Specification (5500-ES-371014), Inner Strand Specification (5500-ES-371009), Outer Strand Specification (5500-ES-371010), Niobium Titanium Alloy Bars and Rods Specification (5500-ES-371015), and Niobium Barrier Material (Reactor Grade I) Specification (5500-ES-371016). All specifications were completed by the end of January 2004, a few days before the BTeV project was cancelled. The cable required for the BTeV C0 IR Quadrupole Magnets was identical to the cable used in the LHC IR Quadrupole Magnet, whose specifications were a mix of original and re-used SSC specifications, with some complications due to this mixed status. The specifications for the conductor to be used in the BTeV IR quadrupoles were originated by modifying the specifications for the LHC IR quadrupoles aiming at a complete and smaller set of documents without redundancy and contradictions, and with updated requirements for quality control. A major modification was introduced in the procurement strategy by procuring the cable (instead of strands and cabling separately) in order to have the vendor fully responsible for all characteristics of the final cable including its mechanical stability (a test was added to specify this characteristic).
The authors are thankful to Ron Scanlan, Luc-Rene' Oberli and Arup Ghosh for their help during the generation of these specifications.

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BTeV C0 IR Quadrupole Magnet Inner Strand Specification[$]

1. SCOPE

This specification establishes the minimum requirements for the manufacture, inspection, test, identification, and delivery of superconducting NbTi composite wire. This material will be used in the manufacture of the inner cable for the BTeV C0 IR magnets.

1.1. Definitions

a) Production unit: Material from a single multifilament billet, which undergoes identical mechanical and thermal processing, and shall be identified as such. A production unit may be less than one full billet. All material from a production unit shall be thermally cycled together in the same furnace, for each and every heat-treatment.

b) Foreign Object: A substance or article alien to the product or assembly that has been allowed to invade the product.

2. APPLICABLE DOCUMENTS

2.1. Applicability

The following documents of the issue in effect on the date of invitation for bids or request for proposal form a part of this specification to the extent specified herein.

2.1.1. Industry and Society Documents

a) ASTM E 243; Eddy Current Testing

b) ASTM F 68; Oxygen-free Copper in Wrought Forms for Electron Devices

2.1.2. Fermilab Documents

a) 5500-ES-371015, BTeV C0 IR Quadrupole Magnet / Niobium Titanium Alloy Bars and Rods

b) 5500-ES-371016, BTeV C0 IR Quadrupole Magnet / Niobium Barrier Material (Reactor Grade I)

c) Appendix I - Critical Current

[$] This specification is similar to SSC inner strand specification, SSC-M35-000014

d) Appendix II - Determination of Filament Size and Spacing

e) Appendix III - Determination of Copper to Superconductor Area Ratio

f) Appendix IV - Sharp Bend Test

g) Appendix V - Determination of Springback Properties

h) Appendix VI - Determination of Normal State Resistance of NbTi Superconducting Wire

2.2. Source of Documents

Any difficulty in obtaining the applicable documents should be referred to the Fermilab Subcontract Administrator.

2.3. Precedence

In the event of conflict between the requirements of this specification and the above applicable documents, this specification shall take precedence. Any such conflict shall be brought to the attention of the Fermilab Subcontract Administrator.

2.4. Deviations and/or Waivers

The Vendor shall provide written request for any deviations or waivers to the technical requirements of this specification prior to proceeding with implementation. Such implementation shall require written authorization by the Fermilab Subcontract Administrator.

3. REQUIREMENTS

3.1. Wire Material

Raw material used in the manufacture of NbTi composite wire shall be procured to the requirements of references 2.1.2a, 2.1.2b and 2.1.1b, and shall be inspected/tested by the Vendor for conformance to those requirements before release for production use.

3.1.1. Non-conforming Raw Material

Material found to deviate from specification requirements, and which is unable to be brought into a state of full and complete conformance by rework, shall be removed from the raw materials inventory.

3.1.2. Raw Material Identification

Each lot of wire raw material shall be uniquely identified to allow all Vendor manufacturing, test, and inspection operation records for finished wire to be traceable to the affected material lot.

3.2. Technical Properties

3.2.1. Conductor Type

The conductor shall be a composite of NbTi filaments in an oxygen-free copper matrix. The NbTi composition shall be Nb47+1wt.%Ti, and shall be high homogeneity grade or equivalent, meeting the requirements of reference 2.1.2a.

3.2.2. Copper-to-Superconductor Ratio (Cu/SC)

The conductor shall have a copper-to-superconductor area ratio of $(1.30 \pm 0.10):1$.

3.2.3. Niobium Barrier

At monofilament assembly size, the Nb barrier shall consist of an area equal to a minimum of 4% of the NbTi area.

3.2.4. Critical Current

The conductor shall have a minimum critical current of 378 A measured at 7 T and 4.22 K, with a critical current criterion of $\rho = 1 \times 10^{-14}\ \Omega$ m, based on the wire cross-section area and with the applied magnetic field perpendicular to the wire axis (see reference 2.1.2c).

3.2.5. Wire Diameter

The conductor shall have a diameter of 0.808 ± .0025 mm.

3.2.6. Filaments

The filament size shall be fixed by design geometry such that at final size the filament diameter is approximately 6.0 μm and the spacing is approximately 1.0 μm. The number of filaments shall not vary by more than 20 filaments from the design value.

3.2.7. Filament Array

a) The multifilament billet shall be assembled using a single stacking procedure. The sub-elements incorporated in the stack shall be hexagonal in shape.

b) The multifilament strand shall have a copper core, which approximates a circular cross section. The core shall be designed for a maximum of 3 % of the total cross sectional area in the final size strand.

c) The outside circumference of the filament array shall approximate a circular pattern.

3.2.8. Resistance at Room and Transition Temperatures

The conductor shall have a maximum normal state resistance (R_{295}) of 60.0 mΩ/m and a maximum transition state resistance (R_{10}) of 0.86 mΩ/m in samples which have been annealed for 2 hours at 270 ^{o}C ± 5 ^{o}C.

3.2.9. Copper Residual Resistivity Ratio

The RRR for wire at final size, equal to R_{295}/R_{10}, is defined by the values of R_{295} and R_{10} given in 3.2.8. The RRR shall be greater than 70.

3.2.10. "n" Value

The wire shall have a minimum "n" value (see reference 2.1.2c) of 30 at 7 T.

3.2.11. Twist Pitch

All wire shall be twisted so the filaments follow the same rotation as a <u>left</u> hand screw thread. The wire twist pitch for wire at final size shall be 13 ± 1.5 mm.

3.2.12. Final Temper

The wire shall not receive any furnace anneals below 3.6 mm in diameter.

3.2.13. Surface Condition

The wire surface shall be free of all surface defects, slivers, folds, laminations, dirt, copper fines, or inclusions. No NbTi filaments shall be visible at 1x under a lighting level of at least 1076 lux.

3.2.14. Mechanical Properties

a) The wire shall survive a sharp bend test, performed in accordance with 2.1.2f, without any sign of cracking at the outside surface of the sharp bend visible at 5x under a lighting level of at least 1076 lux. Filament damage in excess of 1% of design total number of filaments is cause for rejection.

b) The wire shall have a spring back value, measured in accordance with 2.1.2g, of less than 1150 degrees.

3.3. Process Controls

3.3.1. Production Unit

All superconductor strand produced to this specification shall be processed in production units, as defined in 1.1.

Work-In-Process material from a production unit shall remain physically grouped together throughout all phases of the manufacturing process. Any portion of a billet, which becomes separated from its production unit, shall be considered non-conforming and shall be addressed as such.

3.3.2. End Effects

Processing end effects shall be removed prior to yield determination. These defects include areas of distorted cross section due to wire pointing by swaging, foreign material attached as temporary leader, unsteady-state twist material, or areas of distorted filaments that occur at the start and end of an extrusion.

3.3.3. Minimum Lengths

The minimum deliverable piece length shall be equal to the minimum piece length usable to make a minimum cable length as specified in **Spec # 5500-ES-371014** “BTeV C0 IR Quadrupole Magnet Inner and Outer Cable Manufacturing Specification”, after cutting all samples required for tests.

3.3.4. Product Identification

Wire lot identification shall conform to the requirements of section 5.1 of this specification.

3.3.5. Manufacturing Plan

A manufacturing plan shall be established by the Vendor, defined by flow chart, diagram, or narrative; and shall be submitted for review and approval by Fermilab Subcontract Administrator. After production start, any changes to the approved manufacturing plan must be brought to the attention of the Fermilab Subcontract Administrator. No changes shall be implemented without written authorization from the Fermilab Subcontract Administrator.

3.3.6. Control of Manufacturing Machines and Methods

The machines and equipment used to process all superconductor made to this specification shall be identified and documented as part of the Vendor's Quality Plan. No modifications to machines, methods or processes shall be permitted without prior written approval.

4. QUALITY ASSURANCE

4.1. Quality Assurance Plan

Prior to the contract being signed, the Vendor shall submit to the Fermilab Subcontract Administrator, for his/her approval, a documented Quality Assurance Plan, which fulfills all requirements described in the present specification. The Vendor shall also submit to Fermilab Subcontract Administrator, for its approval, a detailed description of the test procedures and the model test certificates, which he proposes to use.

4.2. Responsibility

The Vendor shall be responsible for the performance of all tests and inspections required prior to submission to the Buyer of any of the products for acceptance. The performance of such tests and inspections does not limit the right of the Buyer to conduct tests and inspections to verify conformance to all requirements of this specification. Such Buyer testing and inspection shall be confined to the scope of requirements defined in this specification or approved variations thereof.

4.3. Data Requirements

Data deemed proprietary by the Vendor shall be protected under terms of the contract negotiated between Fermilab and the Vendor. Fermilab and the Vendor shall establish procedures for the control and limited distribution of proprietary data.

4.4. Inspection and Test

Fermilab reserves the right to witness manufacturing steps, tests and inspections established under the Vendor's quality assurance system to demonstrate compliance with this specification.

4.4.1. Wire diameter

The Vendor shall verify the wire diameter by means of a calibrated laser micrometer. All the wire that has been manufactured must be checked on line with a two-axis laser micrometer. The wire must be within tolerance over the full length. The ovality of the strand, defined as the difference between the diameters measured for the two axes, must be less than 3 μm. The Vendor must provide statistical analysis of the laser micrometer measurements, together with the data in electronic format, to the Fermilab Subcontract Administrator.

4.4.2. Copper-to-Superconductor Ratio/Twist Pitch

Test both ends of each continuous length of wire for copper-to-superconductor ratio in accordance with 2.1.2e. During each test verify the presence and the direction of the twist.

4.4.3. Critical Current

a) Test a minimum of three (3) samples from separate continuous deliverable lengths of each billet production unit, in accordance with 2.1.2c. The samples selected for critical current testing shall be the three samples having a Copper-to-Superconductor Ratio closest to the measured production unit mean.

b) Acceptance of the billet production unit shall be contingent on all samples meeting or exceeding the specification minimum critical current. Any billet production unit not meeting this specification will be dispositioned as per section 2.4 of this document.

4.4.4. "*n*" value

Report the "n" value or quality index obtained from the three samples used in 4.4.3, measured in accordance with 2.1.2c.

4.4.5. Resistance Values

Test the billet production unit samples selected for critical current measurement (4.4.3), in accordance with 2.1.2h.

4.4.6. Filaments

Check each billet production unit for filament size and spacing in accordance with 2.1.2d.

4.4.7. Mechanical Properties

a) Perform a sharp bend test on a sample from each continuous length of wire in accordance with 2.1.2f.

b) Perform a spring back test on a sample from each continuous length of wire in accordance with 2.1.2g.

4.4.8. Eddy current test

Each strand must be checked continuously on its overall length by an eddy current method, performed as specified in 2.1.1a, to detect inclusions, voids, cracks and filament defects. Each deliverable piece length shall be free of any inclusion, void, crack and/or filament defect.

4.4.9. Samples for tests at Fermilab

The Vendor shall deliver to Fermilab a 5-m long sample and a 2-m long sample cut at opposite ends of each deliverable piece length. The Vendor shall also deliver to Fermilab the samples mentioned in Appendix I.

4.5. <u>Certificate of Compliance</u>

The vendor shall provide a written statement certifying compliance with the requirements of this specification with each product release for cabling, together with a completed copy of all documentation including all test results. All documentation is to be provided in an electronic form (format should be approved by the Fermilab Subcontract Administrator) also. This documentation shall be provided to the Fermilab Subcontract Administrator after the completion of all tests and inspections, before release for cabling.

5. PREPARATION FOR DELIVERY

5.1. <u>Marking/Identification</u>

Spools and exterior packaging shall be identified with the following information in the order shown:

"Superconducting Wire"
Specification BTeV C0 IR Magnets Inner
Fermilab P.O. NO. ______________
Wire Identification No. ______________
Length ______________ (meters)
Weight ______________ (kg)
Date of Manufacture ______________
Name of Manufacturer______________

5.2. Wire Identification

Each deliverable length of wire shall be assigned a unique identification.

5.3. Winding

Wire shall be level wound so that the wire can be unspooled at a minimum of 30 m/sec without crossovers or kinks. There shall be only one length of wire per spool.

5.4. Packaging

The wire shall be packed in a manner that will protect it from any kind of damage that could occur in shipping from mishandling, exposure to the elements, and/or foreign object contamination. As a minimum, the following is required:

5.4.1. The wire shall be wrapped with a layer of new, clean polyethylene.

5.4.2. The spool shall be bagged in new 0.13 mm (5 mil.) clean polyethylene to protect the wire from foreign object contamination.

5.4.3. The spools shall be secured in the shipping container with the spool flanges maintained in a vertical orientation (axis horizontal) in order to prevent the wire from settling on the spool.

Appendix I - Critical Current

Short sample test method for critical current determination of twisted multifilamentary wire.

1. General Outline: Definition of Critical Current

The V-I curve is determined as a function of increasing current until an irreversible transition or quench occurs. This measurement is carried out in specified external fields, 5.6 T and 7 T for Outer Wire, or 7T and 8T for Inner Wire; applied normal to the wire axis, and in a temperature bath of liquid helium at 4.22 K. For current less than the quench current, the V-I curve is reversible.

The critical current is defined as that at which the resistance per unit length, R/L, is:

$$R/L = (4/\pi D^2)10^{-8} \text{ ohms/m}$$

where D is the wire diameter in millimeters. The effective resistivity of the wire, at I_c, is 10^{-14} Ωm.

2. Sample Testing

The vendor shall measure the critical current of samples selected according to 4.4.3a at B=5.6 T and 7 T, or 7T and 8T, and T=4.22 K. If a temperature of 4.22 K is not possible, measurements may be made at another temperature and a conversion constant must be supplied. The conversion constant must be approved by Fermilab. A 2 m sample of wire adjacent to each length used by the Vendor for critical current measurements shall be sent to the Fermilab Subcontract Administrator. These samples shall be identified by billet number, spool number, original continuous wire length, and purchase order number. Samples may be checked by Fermilab to insure that they conform to all aspects of the specification, both mechanical and electrical.

3. Sample Mounting

The sample wire is most conveniently mounted on a cylindrical former so that it fits in a solenoid magnet (see Section 4 below). Either bifilar or monofilar mounting arrangement may be used, if the procedures outlined below are followed. A non-inductive (bifilar) form will provide adequate length, reduce inductive voltage signals, and provide for ease of connection. Shorter, monofilar mounts may be used if adequately sensitive signal detectors are available; voltage taps and wires should be arranged to minimize the loop. Means must be provided for constraint of mechanical motion without interfering with coolant contact; for example, a G-10 former with grooved location of wire and careful tensioning during mounting, could be used. Care must be taken to ensure that a temperature gradient is not introduced into the region of measurement (gauge length). Care must also be taken in bending the samples, especially at the end of a bifilar sample.

4. Procedure

The sample length (between voltage taps) should be ≥250 mm. This corresponds, typically, to a voltage drop of several microvolts. This is readily measured with the aid of a suitable preamplifier or digital volt-meter. Samples of shorter length may be used if a well functioning nanovolt detection system is available. Equipment must be capable of determining the effective resistivity to a precision of 10%, i.e. 10^{-15} Ωm.

The amplifier signal should be recorded on an X-Y recorder (or if desired in a digital memory device). The V-I curve may be taken either point-by-point (current constant for each measurement) or continuously if induced signals due to ramping are not too large or noisy. Typically, current is supplied by a stable, well-filtered power supply. The current should be measured to a precision of 0.5% and an accuracy of 1%. Use of a low resistance normal metal shunt connected across the sample is permitted provided the resulting correction for shunt current is accurately known and is <0.1%. Electronic circuitry for quench protection is preferable. The quality index, n, is estimated using the equation V = constant x I^n and is evaluated in the resistivity range of 10^{-14} to 5 x 10^{-14} Ωm (see Section 7).

5. Magnetic Field

The external field is most conveniently applied by means of a superconducting solenoid. The field must be uniform over the sample reference length to 0.5%. The direction between field and wire axis must be 90° ± 6° everywhere between the voltage taps. This range of angles corresponds to a variation in I_c of 0.5%. The system should provide a field with a precision of 0.5% and an accuracy of 1%.

6. Temperature Bath Correction

The specification temperature is 4.22 K, that of boiling helium at standard atmospheric pressure. The bath temperature must be recorded with the aid of appropriate thermometry (cryogenic thermometer or vapor pressure of bath) with a precision of ±0.010 K (10 mK). For larger temperature excursions, the "linear T" type of correction should be applied:

$$\frac{I_C}{I_m} = \frac{T_C - T}{T_C - T_m}$$

where T_c is the transition temperature at the specified magnetic field. (T_c= 6.23 K at 7 T.) I_m is the current measured at temperature T_m, and I_c is the critical current at the specification temperature, T=4.22 K.

7. "n" Value Calculation Procedure

A quality index, n, is determined from the V vs. I data using the relationship $V = c \times I^n$. A minimum of 5 data point pairs from the reversible part of the V vs. I data are taken over the resistivitiy range of 1×10^{-14} to 5×10^{-14} Ω-m . Data points taken should cover the range as much as possible, however only data points on the reversible part of the V vs. I curve are allowed. The points taken are plotted on a log-log scale plot and a linear best fit is determined. The slope of the best fit line is reported as "n".

Appendix II - Determination of Filament Size and Spacing

Purpose: To determine the acceptability of filament size and spacing.

Method: Mount a strand sample at the appropriate final size (.648 mm and .808 mm for Outer and Inner respectively) in a suitable mounting material and polish an acceptable cross section. Photograph the sample at sufficient magnification to clearly view individual filaments and the copper between them. Photographs need not capture the whole strand cross section. Verify that the magnification of the micrograph is known and has been calibrated. Measure the mean diameter of 10 representative filaments on the photograph and average. Calculate the actual filament diameter by dividing by the magnification. This is the filament diameter.

Draw a line along 10 filaments which lie in a close packed direction. Measure the distance from the outside to outside of the 10 filaments. This measured distance is equal to 10 d + 9 s, where d is the filament diameter above and s is the filament spacing. Solve for the value of s.

An alternate procedure is to use an Image Analysis technique, reviewed and approved by the Fermilab Subcontract Administrator to determine area fractions, diameters, and spacings.

Appendix III - Determination of Copper to Superconductor Area Ratio

COPPER TO SUPERCONDUCTOR RATIO TEST PROCEDURE

1. Materials List:
   - Pyrex Container
   - Analytical Balance
   - Nitric Acid/Water Solution
   - Ethanol
   - Sodium Bicarbonate
   - 2 gram minimum wire sample
   - Oven
   - Tweezers

2. Label a clean Pyrex container with the spool number for each wire to be tested.

3. Wipe each 2 gram wire sample with alcohol, coil and place in its assigned Pyrex container. Use tweezers to handle wire for the rest of testing procedure. Weigh the wire sample to the nearest .0001 gram and record its weight on the incoming strand inspection form.

4. Place 1 tablespoon of sodium bicarbonate in a container and dissolve in water. Use this to neutralize any acid spills.

   <u>Danger</u> - <u>Nitric acid can cause severe burns and may be fatal if swallowed. Read all labels and use all safety precautions in handling acids.</u>

5. Under fume hood, pour a Nitric Acid/water solution into each Pyrex container to cover the wire samples. Place signs "WARNING-NITRIC ACID."

6. Allow 30 minutes, then check each wire sample to see if all of the copper is etched away. This is done visually and by using tweezers to check for stiffness. Be careful not to cause damage to the sample. Stiffness indicates presence of copper. If copper is present, but acid appears to have stopped etching, pour the acid into a used acid container and add fresh solution.

7. After the copper is completely etched away, pour acid into a well-labeled used acid container. The remains left in the Pyrex container are the superconductor filaments.

8. Gently rinse the filaments in the Pyrex container with water. Be careful not to rinse away loose filaments. Repeat 4-5 times or until thoroughly rinsed.

DANGER: Fine filaments of NbTi are extremely flammable. Keep away from open flame or static electricity sources.

9. Put the Pyrex container containing the sample in the oven at 60°C-70°C for approximately 15 minutes. Gently move the filaments to prevent sticking to the Pyrex container.

10. Dry the filaments for approximately 45 minutes. Weigh the sample to the nearest .0001 gram and record weight on the incoming inspection form. With these weights, you can compute the copper-to-superconductor ratio.

11. Repeat steps 5 through 10. The two measurements should agree to within 5%, if not then continue repeating 5 through 10 until the measurements agree to within 5%.

12. Use the filament weight and copper weight in the following formula:

$$\text{Cu/SC Ratio} = \frac{\dfrac{\text{Weight of copper (Kg)}}{8940\ \text{Kg/m}^3}}{\dfrac{\text{Weight of non-copper components (Kg)}}{\text{Vol \% Nb barrier } (8570\ \text{Kg/m}^3) + \text{Vol \% NbTi } (6000\ \text{Kg/m}^3)}}$$

13. Dispose of filaments in a safe manner to prevent accidental fire.

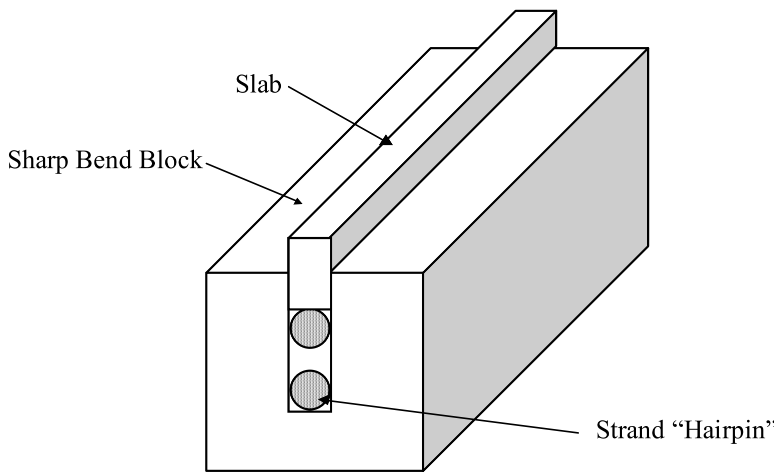
ALTERNATE PROCEEDURE FOR CU/SC DETERMINATION

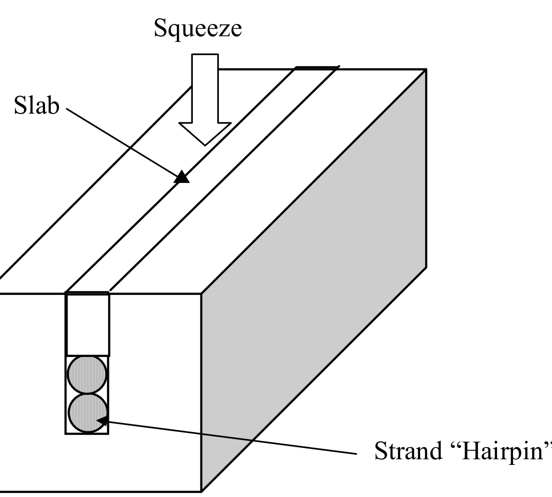
An electrical method can be used by the vendor providing that the vendor's procedure is reviewed and approved by the Fermilab Subcontract Administrator. In addition, provisions must be made, in the procedure, for periodic calibration to the chemical technique.

Appendix IV - Sharp Bend Test

The sharp bend procedure is to simulate the deformation of the strand that may occur during cabling.

1. Fabricate a test fixture consisting of a metal block with a slot and a slab that freely slides in the slot, as indicated in figure below. The slab width should be equal to the strand diameter. The slab should slide freely into the slot without gaps. A drawing will be provided upon request. The vendor can propose his version of the fixture that should be approved by the Fermilab Subcontract Administrator.





2. Cut a length of strand sample approximately 20 cm long. Bend the strand sample in half over a rod approximately 2 mm in diameter as indicated below.

3. Remove the rod and place the bent sample in the slot of the fixture as indicated in the top part of the figure. Slide the slab into the slot of the fixture to squeeze the bent sample to the value of 1.616 mm (inner cable strand) or 1.296 mm (outer cable strand) to obtain a hairpin shape.
4. Examine the bend region at a magnification of at least 10X under a lighting level of at least 1076 lux and verify that the surface of the copper is not cracked, split, or otherwise deformed to prevent successful cabling.
5. Etch the bend region in dilute nitric acid and examine the filaments at a magnification of at least 10X and a lighting level of at least 1076 lux and verify that no filaments have been broken.

Appendix V - Determination of Springback Properties

1. Purpose

This test establishes a standardized method for testing superconducting (S.C.) wire to determine its springback acceptability.

2. Materials Required

2.1 Cut three lengths, 1 m each, of S.C. wire to be tested.
Note: Do not bend wire unnecessarily.

3. Test Equipment

3.1 Springback Test Fixture approved by the Fermilab Subcontract Administrator.

3.2 2 kg weight

4. Test Procedure

4.1 Prepare one end of wire sample with a 13 mm, 90° bend, and tie the other end securely to a 2 kg weight.

4.2 Test the spring fixture to be sure it turns freely.

4.3 Thread the 90° bend through the test fixture and place in the hole in the spring winder with the locking pin in place.

4.4 Tighten the wire.

4.5 Make sure the 90° bend is not affecting the "Zero" reading and the wire is tangent to the spring winding shaft.

4.6 Set "Zero" on the degree wheel.

4.7 Hang the 2 kg weight over the end of the table. Release the clamp. Hold the spring winder handle and pull the locking pin.

4.8 Wind 10 complete turns and replace locking pin. Then tighten wire clamp.

4.9 Hold spring handle and remove locking pin. Gently let the spring unwind and note the number of revolutions.

4.10 Once the spring has stopped, gently touch the spring handle to make sure the spring is at equilibrium and has reached its full springback. Do not unwind the spring.

4.11 Note and record the total number of degrees of springback.

4.12 Cut the sample at the wire clamp and the 90° bend.

4.13 Carefully slide the spring winder out of its bearings and remove the sample.

4.14 Measure and record the inside diameter, label the sample and store in archives.

4.15 Three sections of each wire sample shall be measured and reported.

Appendix VI - Determination of Normal State Resistance of NbTi Superconducting Wire

1. General Outline; Definition of Residual Resistance Ratio

This method covers the measurement of electrical resistance of NbTi multifilamentary composite wire, which is used to make high current superconducting cables. The resistance per unit length is determined at room temperature (295 K) and just above the transition temperature (T_c~9.5 K). These quantities are designated R_{295} and R_{10}, respectively, and are measured with an accuracy of 0.5%. The ratio R_{295}/R_{10} is defined to be the residual resistance ratio, RRR.

2. Apparatus Description

A four wire method is used to determine the resistance. The wire sample is mounted on a probe which may be used for superconducting critical current measurements. It has leads which are suitable for carrying the required current 0.1 to 0.5 A from room temperature into a liquid helium bath, and potential leads for measuring the voltage drop across a measured length of the test specimen. The probe should be mounted so that the test specimen can conveniently be raised and lowered through the level of a helium bath.

Voltage drops are measured with a digital voltmeter of 0.5µV resolution. It is helpful during the low temperature measurement to use an X-Y recorder simultaneously with the digital voltmeter, with Y set to voltage and X to time (see Section 4 below).

Current is provided by a well- regulated and filtered DC power supply. It is measured by a shunt of 0.5% accuracy.

In the room temperature measurement, a temperature measuring device of 0.1°C accuracy is used to determine the ambient temperature.

3. Sample Mounting

The test specimen is attached to a holder. The ends are soldered to the copper terminations of the current leads over a minimum length of 25 mm. Voltage taps are soldered to the specimen at a distance of at least 25 mm from the current joint. Voltage taps are soldered to the specimen at a separation distance of at least 25 mm from each current lead connection. It is advisable that these taps be in the form of fixed pins so that the test length be constant throughout a series of measurements. In order to assure an accuracy of 0.2% the voltage tap length should be .5 m or more. The voltage leads should follow the sample in a non-inductive fashion so as to minimize noise pickup. Alternatively, the sample may be wound non-inductively on the form.

4. Procedure

Room temperature measurements are made at currents which are a compromise between the requirements of sensitivity and negligible ohmic heating. Voltage readings are taken for forward and reversed current and averaged.

Low temperature measurements are made in a helium dewar. The probe is withdrawn from the bath so that the lowest point of the specimen is a few centimeters above the liquid helium bath level while measuring current is flowing. As the sample warms, the voltmeter reading will go suddenly from zero to a finite value corresponding to its normal state resistance. The latter is substantially independent of temperature from the transition temperature, T_c, to 15 K, so that the voltage remains constant long enough to be read and is recorded. In addition, it is unnecessary to determine the exact temperature as long as it is assured that the low temperature measurement is made while the voltage is nearly constant. With a reasonably designed probe and former, it may take 1 or 2 seconds for the specimen to go normal. The resistance will remain in the residual resistance region for several seconds. When the X-Y recorder is used, a series of abrupt voltage changes are recorded as the specimen is alternately raised and lowered through the helium bath level. The height of these steps should be reproducible. At least two cycles with similar residual resistances shall be performed to complete the R_{10} measurement.

5. Room Temperature Correction

Normally occurring room temperature variations may produce significant variations in the measured resistance. Designating this resistance as R_m and the ambient temperature as T_m (°C), the resistance at the reference temperature of 295 K is calculated as follows:

$$R_{295} = R_m/[1 + .0039\ (T_m - 22)]$$

The effect of the NbTi is neglected for the purpose of this correction.